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An Analysis of Variance of the Countermine Experiment (CME)

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PREFACE

This document was prepared under Central Research Project 9001-139. It is an analysis of variance of the combat outcomes from the Countermine Experiment, which was conducted at Fort Knox, KY in July, 1996, by the Night Vision Electronic Sensors Directorate, Ft. Belvoir, VA and the US Army Engineer School, Ft. Leonard Wood, MO. The author would like to acknowledge the assistance of Mr. Paul Monday, of Lockheed-Martin Corporation, who processed the protocol data units and supplied the raw data from the experiment. Finally, the author would like to thank the IDA reviewers, Dr. David L. Randall, Director System Evaluation Division, Dr. Phillip Gould, Dr. Eric W. Johnson, and Mr. Warren K. Olson for their careful readings of the manuscript and their helpful suggestions.

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PART 1

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

A. PURPOSE

The purpose of this document is to describe the combat outcomes of the Countermine Experiment (CME), a Distributed Interactive Simulation (DIS) exercise conducted at the Mounted Warfare Testbed at Ft. Knox, KY, in July 1996. This analysis is based on the fact that the CME was structured on a 2^3 factorial design, which suggests a specific linear model as the predictor of experimental outcomes. Classical analysis of variance is used to determine the significant factors in this model. These factors are analyzed in terms of the context of the experiment.

The CME was conducted under the direction of the Night Vision Electronic Sensors Division, Ft. Belvoir, VA, and the Engineer Battle Testbed, Ft. Leonard Wood, MO. It entailed manned and unmanned simulators in a company-level armored engagement in which antitank mines and countermine equipment played a fundamental role. The purpose of this test was to gain insight into the potential utility of new land mine detection and neutralization technologies.

A shorter and more elementary version of the document was prepared as a working paper under task T-D1-1230.

B. OVERVIEW OF CME TESTS

1. Technologies

Three innovative countermine technologies were explored in CME: the Airborne Standoff Minefield Detection System (ASTAMIDS), the Ground Standoff Minefield Detection System (GSTAMIDS), and the Explosive Standoff Minefield Breacher (ESMB). The first, ASTAMIDS, is a sensor-laden Unmanned Aerial Vehicle (UAV) designed to detect land mines emplaced in conventional string, lattice, or scatter patterns. Two versions of this system are under consideration: one with a passive IR sensor, and another with an active laser and a passive IR sensor. Sensor data are transmitted from the UAV to a mobile ground station for processing. ASTAMIDS flies at 80 knots at an

altitude between 100 and 300 meters. Its sensor footprint is 65 meters wide (at an altitude of 100 meters). This system was modeled with a 75% probability of detecting a given antitank (AT) mine swept by its sensor.

The second technology is the Ground Standoff Minefield Detection System. This is an experimental system consisting of a configuration of ground penetrating radar, along with ultraviolet and X-ray backscatter detection sensors. It is designed to detect both magnetic and nonmagnetic antitank mines. In CME, GSTAMIDS was modeled with a 40 meter standoff range and a 40 x 60 square meter resolution cell. The probability of detection of an AT mine within a cell was 75%; however, three or more mines needed to be detected before GSTAMIDS reported that a cell contained mines.

The third and final technology explored in CME was the Explosive Standoff Minefield Breacher (ESMB). This system consists of a rocket-ferried 5 x 145 square meter net containing shape charges capable of neutralizing surface and buried land mines. The ESMB was mounted on a trailer and towed by an M1A1 and had a standoff range of 45 meters in CME. As modeled, the system had a 95% probability of neutralizing any mine covered by its net.

2. Trial Conduct

The CME consisted of 32 trials, conducted over a 4-week period, in which each possible combination (eight in all) of the three technologies was tested four times. The four replications of each mix of countermine equipment were run on distinct terrain tracts, or regions, of the Fort Knox Military Reservation (a simulated terrain database). Formally, this is an example of a 2^3 factorial experimental design in which three factors are each tested at two levels with four repeated measurements. Each technology appeared symmetrically in half the trials. For example, half had ASTAMIDS data (collected in a preliminary phase of the experiment), half did not. One quarter had both ASTAMIDS data and GSTAMIDS; one quarter had neither; one eighth had all three technologies. In trials without ASTAMIDS data, Blue received no aerial detection intelligence. In trials without GSTAMIDS, Blue had no ground detection system. In trials without ESMB, Blue had access to a conventional breaching system, the Armored Vehicle Launched MICLIC (AVLM). In all trials, Blue had use of tank mounted plows and rollers for mine clearing operations.

In each trial, the Blue force consisted of one M1A1 armored company, an M113A2 engineering platoon, and an additional M1A1 platform for the breaching system

or ground surveillance system or both. The armored company commander's M1A1 and one vehicle from each Blue platoon (the platoon leader's) were manned; all the others were Modular Semi-Automated Force (ModSAF) entities. Five of the unmanned M1A1s were outfitted with either plows or rollers. In addition, Blue was supported by an M107 artillery unit. OPFOR consisted of two ModSAF BMP2s and one T80. OPFOR artillery was represented by the ModSAF "Bomb Button," a mechanism through which an operator can deliver ordnance without a tube representation. Also, between four and six 200 m x 100 m minefields, each containing 140 antitank mines, were deployed in each trial.

The objective in each trial was determined by a Blue battalion commander. This was conveyed to the Blue company commander in a series of OP-ORDERs and FRAGOs. The company commander, in turn, conveyed orders to his unit in pre-trial briefings. Trials were conducted under the supervision of the Blue battalion commander. In particular, he decided when the objective was attained and when each trial was complete.

Data were recorded by ten research assistants, video tapes, the battalion commander, ModSAF plan view imagery, and—most relevant to this paper—electronic loggers that captured DIS protocol data units. In addition, after-action reviews and weekly summary sessions provided "feed back" and subjective insight.

C. SUMMARY OF RESULTS AND CONCLUSIONS

This paper analyzes three measures: Blue losses to mines, to direct and indirect fire combined, and losses to all agents combined. A loss in this context means any level of destruction: catastrophic, mobility, or firepower (without double counting, of course). Of specific interest is the impact of the various mixes of countermine equipment on these losses. In particular, an attempt will be made to determine the most significant factors affecting (reducing or increasing) Blue losses by computing analysis-of-variance (ANOVA) tables for the main factors in this test and their interactions. Little attention will be paid to OPFOR losses as there were only three OPFOR vehicles played in each trial. Generally—with only two exceptions—either two or three of these were destroyed (average OPFOR loss was 2.5 vehicles).

This analysis differs from IDA Paper P-3300, "Analysis of an Army Countermine Top Level Demonstration - The Countermine Experiment," in several ways. First, in the present document, losses to direct and indirect fire are analyzed explicitly. Secondly, the impact of scenarios is examined (as a covariate to the basic factorial design). Finally, the

earlier IDA Paper includes an analysis of temporal measures, whereas, in this document, attention is confined to vehicular losses.

Figure 1 is borrowed from the main body of this report and summarizes Blue losses for each combination of countermine equipment. It gives some indication of the impact of ASTAMIDS on reducing Blue losses, but also suggests some "uneven" behavior among the various countermine systems. For example, the reduction in losses to mines when AVLM and ASTAMIDS data are used in conjunction does not carry through to the cases in which ESMB and ASTAMIDS are used together.

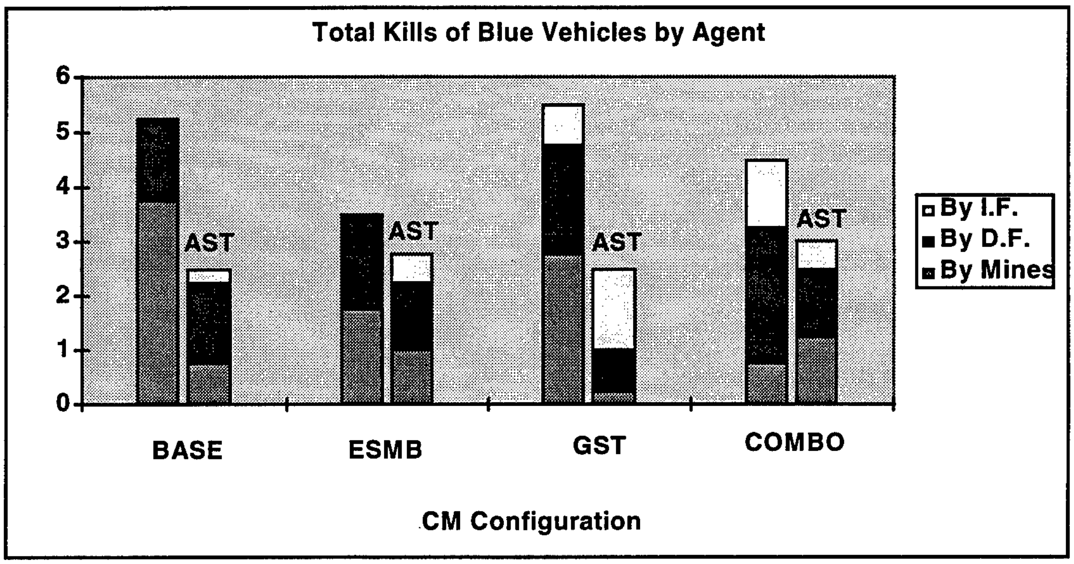

Figure 1. Blue Vehicle Losses by Agent

Since the CME was conducted as a classical factorial experiment, the expected outcomes displayed in Figure 1 are determined by a specific linear model. In the case of a 2^3 factorial, that model is

$$E(y_{ijkn}) = u + a_i + b_j + g_k + ab_{ij} + bg_{jk} + ga_{ki} + w_{ijk}$$

where 'u' represents an overall mean effect; the variables with a single subscript refer to contributions from the principal factors (aerial surveillance, breaching system, and ground surveillance); and the variables with more than one subscript are cross terms or interactions among the principal factors (ab_{ij}, bg_{jk}, and ga_{ki} represent interactions between aerial surveillance-breacher, ground surveillance-breacher, and aerial-ground surveillance interactions respectively; w_{ijk} represents interaction among all three factors). All indices

take on the value zero or one (with zero connoting the "low level" of a factor), and all variables are subjected to the constraint that any sum over the range of any subscript is zero, e.g. ab_{0j}.+ $ab_{1j} = 0$.

By fitting the above model to each of the three measures of interest, the sets of coefficients in Table 1 are derived. For example, the expected number of losses to direct and indirect fire with AVLM, GSTAMIDS, but no ASTAMIDS is:

$$2.156 + 0.281 - 0.094 + 0.469 - 0.219 - 0.0313 + 0.344 - 0.156 = 2.75,$$

which corresponds to the fifth vertical bar in Figure 1, above. Note, $g_1 = 0.469$ appears in the expression instead of $g_0 = -0.469$ because GSTAMIDS was used in this group of trials.

Table 1. Regression Coefficients for Main Effects and Interactions

	Regression Constant or Coefficient							
Blue losses	**u**	a_0	b_0	g_0	ab_{00}	bg_{00}	ga_{00}	w_{000}
To Mines	1.53	0.719	0.344	0.281	0.656	0.094	0.219	-0.094
To DF+IF	2.156	0.281	-0.094	-0.469	-0.219	0.0313	-0.344	0.156
To All Agents	3.69	1.0	0.25	-0.187	0.438	0.125	-0.125	0.0625

The ANOVA tables developed in the body of this report indicate that a_i (aerial surveillance) and ab_{ij} (interaction cross term between aerial surveillance and breaching system) are significant with respect to losses to mines, whereas only a_i is significant with respect to total losses. The "uneven" behavior mentioned earlier in the discussion of Figure 1 and the significance of ab_{ij} in the linear model are closely related. The suggestion is that ASTAMIDS data caused a major improvement in runs where AVLM was available, but had a lesser effect when ESMB was available. This may be due to the predilection of the commander to circumvent minefields in runs with AVLM and ASTAMIDS intelligence, which seems not to be present when ESMB is available. Indeed, with AVLM and ASTAMIDS, Blue breached minefields only twice in eight runs; without ASTAMIDS Blue attempted five breaching operations in the same number of opportunities. In contrast, Blue launched ESMB in five runs with ASTAMIDS and in five runs without.

None of the regression terms corresponding to principal factors is significant with respect to losses to direct and indirect fire unless the variance due to different areas on which the replications took place is taken into account. When this is done, then g_k, ground surveillance, becomes significant in the sense that GSTAMIDS is associated with increased losses to direct and indirect fire (see discussion below).

By examining the regression coefficients in Table 1, or by referring to Appendix A for the data supporting Figure 1, one determines that the average number of Blue vehicles lost was 3.69 per trial. When ASTAMIDS intelligence was available, losses dropped to 2.69 per trial. Without ASTAMIDS, Blue lost 4.69 vehicles on average. Losses to mines as well as losses to direct and indirect fire were reduced with ASTAMIDS. Losses to mines decreased from 2.25 to 0.81, while losses to direct and indirect fire dropped from 2.44 to 1.88 per trial. While it would be reasonable to apply t-tests to determine the significance of the difference in means (for example the difference in mean losses for the trials with and without ASTAMIDS is significant well below the 10% level), the analytic route followed here will center on the linear model, instead.

The use of other technologies (other than ASTAMINDS) did not always result in fewer Blue losses. For example, with GSTAMIDS Blue lost 3.88 vehicles per trial, but only 3.5 without. While Blue losses to mines were reduced with GSTAMIDS (1.25 compared to 1.8), losses to direct and indirect fire increased (2.63 with, and 1.69 without). Similarly, while Blue losses overall were less with ESMB than with AVLM (3.94 and 3.44, respectively), losses to direct and indirect fire were slightly higher with the newer technology (2.25 compared to 2.06). Losses to mines were considerably less with ESMB (1.19) than with AVLM (1.88). Table 2 summarizes the mean number of kills of Blue vehicles by OPFOR agents. The first row shows the technology available in the 16 trials over which the kills were averaged.

Table 2. Mean Blue Losses by Agent Versus Countermine System

Blue Losses	AST	No AST	ESMB	AVLM	GST	No GST
By mines	0.81	2.25	1.19	1.88	1.25	1.81
By D.F.+ I.F	1.88	2.44	2.25	2.06	2.63	1.69
Total	2.69	4.69	3.44	3.94	3.88	3.5

The impact of tactics, that is minefield avoidance or minefield breaching, was analyzed as a covariable to the basic linear model (that is, it was included in a second set of computations as a regression variable without interaction with any of the terms associated with the principal factors). Mentioned earlier as a possible explanation for interaction between the breaching systems and aerial surveillance, breaching was attempted or initiated in 19 of the 32 trials. Bypassing was conducted in the remaining 13. Nine "bypasses" were conducted with ASTAMIDS, and four were conducted without. Similarly, four "bypasses" were conducted when ESMB was available and nine were conducted with AVLM. Unsurprisingly, aerial surveillance data and type of breaching system were the most important factors determining tactics.

Blue losses in trials in which breaching was attempted averaged 4.37 vehicles, compared to 2.7 vehicles in trials in which minefields were bypassed. Losses to direct and indirect fire was essentially the same for both (about 2.15). Unsurprisingly, losses to mines were much less in those trials in which bypassing occurred (0.54 compared to 2.2). The fact that any occurred at all was apparently due to poor information about minefield locations, the inability of vehicles to navigate gaps between fields, or simply the inability to avoid fields due to their layout and the terrain. Regarding the last possibility, all losses to mines during attempted bypass operations occurred in Area #1, a narrow corridor that was effectively blocked by mines.

Finally, learning was analyzed through stepwise regression and did not appear to have an impact, even when the effects of terrain and tactics were included. On the other hand, geographic areas were significant. In particular, Area #1 stood out from the other subregions as more costly in terms of both losses to mines and to direct and indirect fire. The explanation of why this was the case is unclear. One plausible explanation is the fact that, since replications were run in order by area, Area #1 was the first region on which each new mix of equipment was used (also, Area #1 was topographically more restrictive). There was only one exception to this procedure in the test. So, perhaps learning did take place on a "local level": with respect to the four replications of each mix of countermine equipment.

There are three points that stand out from the analyses of variance of CME data: ASTAMIDS intelligence data is a significant factor in reducing losses due to mines and all agents combined. Secondly, the use of GSTAMIDS is costly with respect to losses from direct and indirect fire, especially in breaching operations. The third and final point

is that there appears to be a strong interaction—with respect to Blue losses to mines—between aerial surveillance and the explosive breaching system.

Taking these points one at a time, the benefit to Blue ascribed to ASTAMIDS data is due, at least in part, to the fact that bypassing (as opposed to breaching) minefields was employed as a tactic at a relatively high frequency when ASTAMIDS data were available. Breaching was costly: overall Blue losses were fewer when minefields were avoided.

Regarding the second point, it is difficult to say precisely why Blue losses to direct and indirect fire increased when GSTAMIDS was deployed. However, it is very likely that Blue vehicles were more exposed while GSTAMIDS was used to find minefield boundaries and gaps between fields. Interaction between aerial surveillance and the explosive breaching system (the third point) with respect to mines was due to the fact that bypassing was the preferred tactic when AVLM and ASTAMIDS data were available. The possibility of a tendency (perhaps ascribable to the desire to exercise a new system) to breach when ESMB was on hand should not be discounted. When tactics are taken into consideration, ESMB reduces losses to mines, however.

In terms of the linear model, only aerial surveillance is significant with respect to losses to all agents, while aerial surveillance and the interaction between aerial surveillance and breaching system are significant with respect to losses to mines. When the variance due to replications (scenario areas) is taken into account, ground surveillance becomes significant with respect to losses to direct and indirect fire. Finally, when tactics and scenario areas are included as covariables to the basic model, the resulting significant factors with respect to losses to mines are: tactics, scenarios, breaching systems, and the interaction between aerial surveillance and breaching system. With the exception of the interaction, the same factors are significant with respect to losses to all agents. Finally, ground surveillance and scenario area are significant with respect to direct and indirect fire losses.

The issues raised in this analysis of CME should be investigated in greater detail. An appropriate research mechanism might be a constructive model in which large numbers of trials can be generated. It is highly recommended that future test designs include tactics (breaching - bypassing) as a principal factor.

Finally, the conclusions reached in this analysis largely agree with those in IDA Paper P-3300. A principle difference is the fact that the current analysis identifies GSTAMIDS as a significant factor in Blue losses to direct and indirect fire. Another is the

identification of the impact of Scenario Area 1. Both studies, however, suggest ASTAMIDS data was a significant factor in reducing Blue losses to mines and all agents combined.

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PART 2

ANALYSES

I. CONDUCT OF THE TEST

A. PRELIMINARY PHASE

The CME was conducted in two phases: a 1-week preliminary phase in May and June 1996, in which aerial surveillance data were collected and a 4-week combat phase in July 1996. The preliminary phase was a non-combat activity in which ASTAMIDS missions were flown (simulated) over the regions in which the July test was to be conducted. Minefields in the preliminary phase were emplaced in exactly the same location as those in the principal phase and detection data collected by ASTAMIDS were provided to the Blue force in the appropriate trials. The purpose of this preliminary phase was to perform intelligence gathering missions "off-line" in order to conserve time during the principal phase of CME as well as replicate the execution of surveillance activities in advance of combat missions.

B. EQUIPMENT

The CME combat phase was a free play exercise in which a Blue armored company, supported by an engineering platoon and artillery, engaged a small OPFOR unit supported by minefields and artillery. The Blue force consisted of one M1A1 armored company, an M113A2 engineering platoon, and an additional M1A1 platform for the breaching system or ground surveillance system or both. Five of the Blue vehicle simulators had human operators: the armor company commander's M1A1 and each of the Blue platoon leader's (three tank and one engineer) vehicles. The unmanned portions of the engineering platoon and each tank platoon were simulated as Modular Semi-Automated Force (ModSAF) entities. Each was controlled by an individual operator and a separate workstation. OPFOR vehicles, two BMPs and one T80 were likewise controlled by one operator and a single workstation.

The equipment available to each side is listed in Table 3, below. Five of the unmanned M1A1s were equipped with either rollers or plows. In addition to these mechanical mine clearing systems, Blue also had one explosive mine clearing system: either the trailer mounted Explosive Standoff Mine Breacher (ESMB), or the tank-

mounted Armor Vehicle Launched Mine Clearing Line Charge (AVLM). Two surveillance systems were available to Blue (depending on the trial as described in the trial matrix below). These were the Airborne Standoff Minefield Detection System (ASTAMIDS) and the Ground Standoff Minefield Detection System (GSTAMIDS).

Table 3. Blue and OPFOR Equipment

Equipment	Blue	OPFOR
Armor	13 M1A1s (3 with plows, 2 with rollers)	1 T80 2 BMP2
Engineer vehicles	4 M113A2	
Mines		4 to 6 minefields 140 AT 80 AP (each field)
CM equipment	AVLM ESMB GSTAMIDS ASTAMIDS	
Artillery	M107 unit	Bomb button

Blue countermine systems other than rollers, plows, and AVLM were simulated as Dial-a-Tank entities, developed by *MäK* Technologies. Rollers, plows, and AVLM were simulated in ModSAF. Minefields were created and controlled by the Comprehensive Mine Simulator (CMS).

In addition to their crews, each manned vehicle contained a research assistant who was assigned to take notes throughout the trial. Research assistants were also assigned to each of the ModSAF operators. The battalion commander, who served as coordinator and overseer of the CME, also recorded notes throughout the trial. In addition to these notes, data were recorded on video tape and, most importantly for this paper, by data logger software.

C. PREPARATION

Trials were conducted twice a day over a 4-week period. Pre-briefs were conducted prior to each run. These meetings consisted of a lecture by the company commander to the M1A1 and M113 crews in which he described the objective, tactics, and intelligence regarding and minefield locations and OPFOR armor. These sessions took place in the presence of the battalion commander and represented the company commander's synthesis of the battalion commander's fragmentary orders (FRAGOs).

The trials began immediately after the pre-briefs and were conducted under the direction of the battalion commander. It was his responsibility to enforce ground rules and determine stopping conditions. The battalion commander also conducted after-action reviews in which soldier "feedback" was solicited and recorded.

D. TEST MATRIX

The experiment consisted of 32 simulation runs in which 8 variations (all possible combinations of three factors) of countermine equipment were available to Blue. A given mix of equipment was used in four successive runs, each of which took place in a different geographical area of the Ft. Knox terrain database. The countermine equipment consisted of one of two explosive breaching devices, AVLM or ESMB, a ground-based mine detection system, GSTAMIDS, and an aerial surveillance system, ASTAMIDS. The equipment mixes were:

1. AVLM alone
2. AVLM and ASTAMIDS
3. ESMB alone
4. ESMB and ASTAMIDS
5. GSTAMIDS and AVLM
6. GSTAMIDS, AVLM and ASTAMIDS
7. ESMB-GSTAMIDS combined
8. ESMB-GSTAMIDS with ASTAMIDS.

Table 4 is a test matrix that indicates the order in which the tests were conducted and the various mixes of equipment that were available to Blue in each run. With the exception of the first, each row corresponds to a different week of the exercise, while the

adjacent columns correspond (roughly) to mornings and afternoons during the test period. In a typical week, eight runs would take place with one day reserved for make-ups and administrative activities.

Table 4. Test Matrix

					AST	AST	AST	AST
	area 1	area 2	area 3	area 4	area 1	area 2	area 3	area 4
AVLM (base case)	29	30	31	32	1	2	3	4
ESMB	5	6	7	8	12	9	10	11
AVLM-GST	13	14	15	16	17	18	19	20
ESMB-GST	21	22	23	24	25	26	27	28

In the parlance of the test conductors, each row was referred to as a "vignette." These were intended to correspond to successive weeks of the test; however, some repetition of base case runs took place during fourth week (hence the irregular numbering). Thus the runs in the first row in which AVLM was the breaching device were referred to collectively as "vignette 1." The runs in which ESMB and GSTAMIDS were used together were referred to as "vignette 4."

E. FACTORIAL DESIGN

The test matrix falls into what is classically known as a "2^3 factorial" design. Three factors, the breaching device, ground surveillance, and aerial surveillance, each appear in two "levels." In this scheme AVLM and ESMB can be thought of as the low and high levels of explosive breachers, respectively. The low level of ground surveillance is associated with not having GSTAMIDS, while the high level is the condition of having GSTAMIDS available. Similarly, the low and high levels of aerial surveillance correspond to not having or having ASTAMIDS data, respectively. Finally, the four geographic areas in which each run is repeated with identical equipment mixes corresponds to taking repeated measurements (4) for each combination of the "principal factors."

Pictorially, this test design can be represented by a cube. Each vertex represents or corresponds to a specific mix of countermine equipment (again, principal factors). Thus, in Figure 2, the top plane corresponds to the high level of aerial surveillance—those runs in which ASTAMIDS was used—while the back plane represents those in

which ESMB was available. Similarly, the rightmost plane corresponds to the high level of ground surveillance.

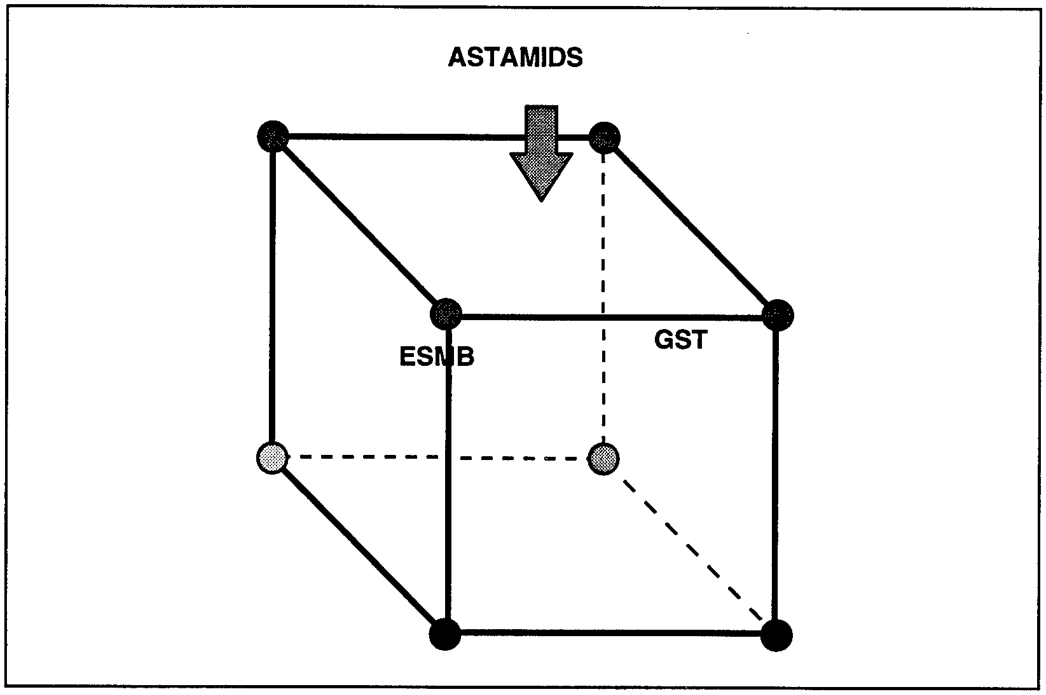

Figure 2. Test Design

The utility of this representation is the opportunity to analyze outcomes (measures) both in terms of the contribution of each of the principal factors and in terms of the interaction of these factors with one another. This is particularly simple to do because the test design is balanced (four repeated measures take place at each "vertex") and can easily be described in terms of a standard ANOVA table for a given Measure of Effectiveness (MOE).

From a mathematical perspective, the expected outcome of a given run (or the value associated with a given vertex on the cube) is

$$E(y_{ijkn}) = u + a_i + b_j + g_k + ab_{ij} + bg_{jk} + ga_{ki} + w_{ijk}$$

where 'u' represents an overall mean effect, the variables with a single subsript refer to contributions from the principal factors (aerial surveillance, breaching system, and ground surveillance), and the variables with more than one subscript are cross terms or interactions among the principal factors. The difference between the expected outcome

and the actual outcome, y_{ijkn} , is the random error, which is assumed to be normally distributed with zero mean and unknown variance.

Since there are only two levels of each factor in our model, each subscript takes on only two values (zero and one, say). Further, the indexed variables are constrained by the requirement that their sum over the range of a given index is zero (essentially to avoid over-parameterization and allow the analyst to separate principal effects in the presence of interactions). That is,

$$\Sigma\, a_i = \Sigma\, b_j = \Sigma\, g_k = 0$$

For multiply-indexed variables, such as ab_{ij}, the constraint is $\Sigma_i\, ab_{ij} = \Sigma_j\, ab_{ij} = 0$.

II. ANALYSES

A. BLUE LOSSES

Throughout most of this paper, the MOE of interest will be the number of Blue vehicles killed in a trial or set of trials. As the Opposing Force (OPFOR) had at its disposal direct fire weapons (T80s and BMPs), indirect fire, and mines, it will sometimes be of interest to group Blue losses by agent, as in Figure 3. In most cases, however, kills by direct and indirect fire will be grouped together and distinguished from kills by mines. Also, the term "kills" will refer to all levels of Blue vehicular losses. Thus, the number of "kills" in a single trial will refer to the sum of mobility, firepower, combined mobility and firepower, and catastrophic kills—with at most only one level of kill per vehicle entering the tally.

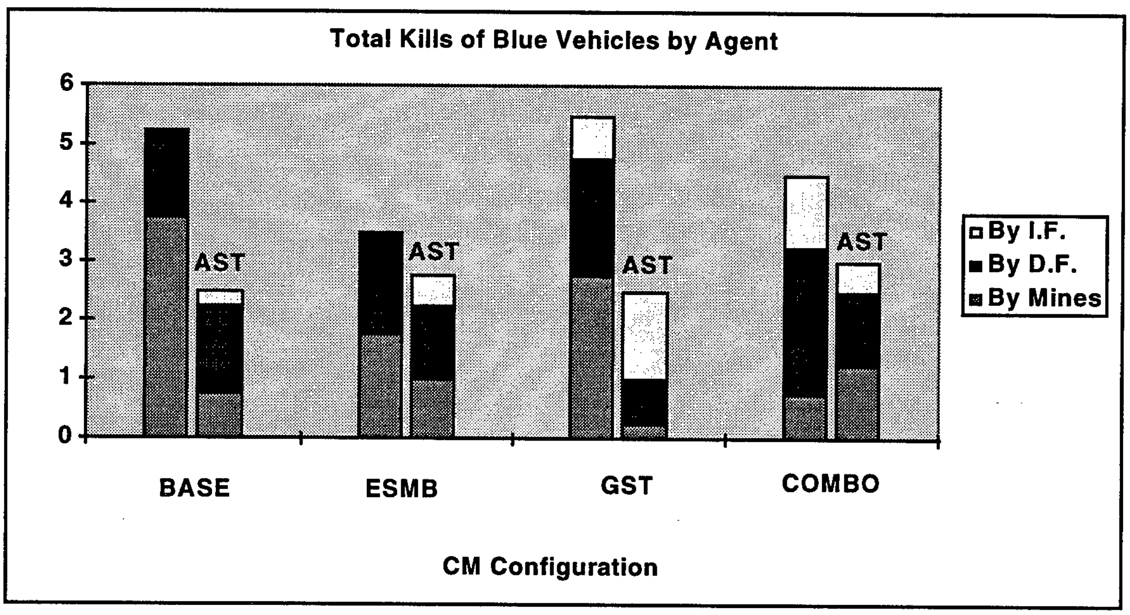

Figure 3. Blue Losses by Agent

Through most of this analysis, however, we will be interested in the average number of kills occurring in the four runs in which countermine equipment was held fixed. In that vein, Figure 3 shows average Blue losses by agent for all the mixes of

countermine equipment. Reading left to right, the graph corresponds to countermine conditions (CM) present in vignettes—or weeks—one through four.

Recall from the Executive Summary, where this figure was first presented, that the average number of Blue vehicles lost was 3.69 per trial. When ASTAMIDS intelligence was available, losses dropped to 2.69 per trial. Without ASTAMIDS, Blue lost 4.69 vehicles on average. Losses to mines as well as losses to direct and indirect fire were reduced with ASTAMIDS. Losses to mines decreased from 2.25 to 0.81, while losses to direct and indirect fire dropped from 2.44 to 1.88 per trial. (Recall that each bar in Figure 3 represents the average of four runs.)

Table 5, below, groups the data presented in Figure 3 so that the effects of the presence versus the absence of CM systems can be compared, system by system. For example, one sees that the average Blue loss without ASTAMIDS is about 4.7 vehicles, while with ASTAMIDS, losses are reduced to about 2.7 vehicles. Similarly, there is a reduction in loses to mines from 2.25 to 0.81 vehicles when ASTAMIDS is deployed. While two-tailed t-tests show both of these to be significant reductions, it will be the focus of this paper to analyze outcomes in terms of ANOVA tables and not comment too heavily on the significance of the difference in means.

Table 5. Mean Blue Losses by Agent Versus Countermine System

Blue Losses	AST	No AST	AVLM	ESMB	GST	No GST
By mines	0.81	2.25	1.88	1.19	1.25	1.81
By D.F.+ I.F	1.88	2.44	2.06	2.25	2.63	1.69
Total	2.69	4.69	3.94	3.44	3.88	3.5

Interestingly, there is an increase in total losses from 3.5 to 3.88 vehicles when GSTAMIDS is deployed. Although there is a decrease in losses to mines, losses to direct and indirect fire more than make up the difference. The latter fluctuation, from 1.69 to 2.63 vehicles, is likely due to the amount of time Blue forces are stationary and exposed to indirect fire while minefields are probed with GSTAMIDS. While neither the increase in losses to all agents nor the decrease in losses to mines is significant, the change in [direct plus indirect] fire losses is. A two-tailed paired comparison shows this difference in means is significant below the 10% level.

B. OPFOR LOSSES AND LOSS EXCHANGE RATIO

OPFOR deployed only three vehicles in each run: one T80 and two BMP2s. OPFOR artillery was controlled by the ModSAF "Bomb Button," a mechanism that was invulnerable to Blue countermeasures and controlled by the ModSAF operator. The variability of OPFOR losses was very small. OPFOR lost two vehicles in 12 cases, all 3 vehicles in 18 cases, and 1 vehicle in each of the remaining 2. The mean was 2.5 with standard error of the mean approximately equal to 0.11. Thus the distribution of OPFOR losses is not particularly interesting and the graphs of Blue losses essentially relates all the information regarding the exchanges between OPFOR and Blue.

Having stated that OPFOR losses do not provide very interesting statistics, a graph (Figure 4) of the loss exchange ratios is included (Blue losses/OPFOR losses) for completeness. As expected, it follows the general pattern of Blue losses as shown in the earlier graph, Figure 3.

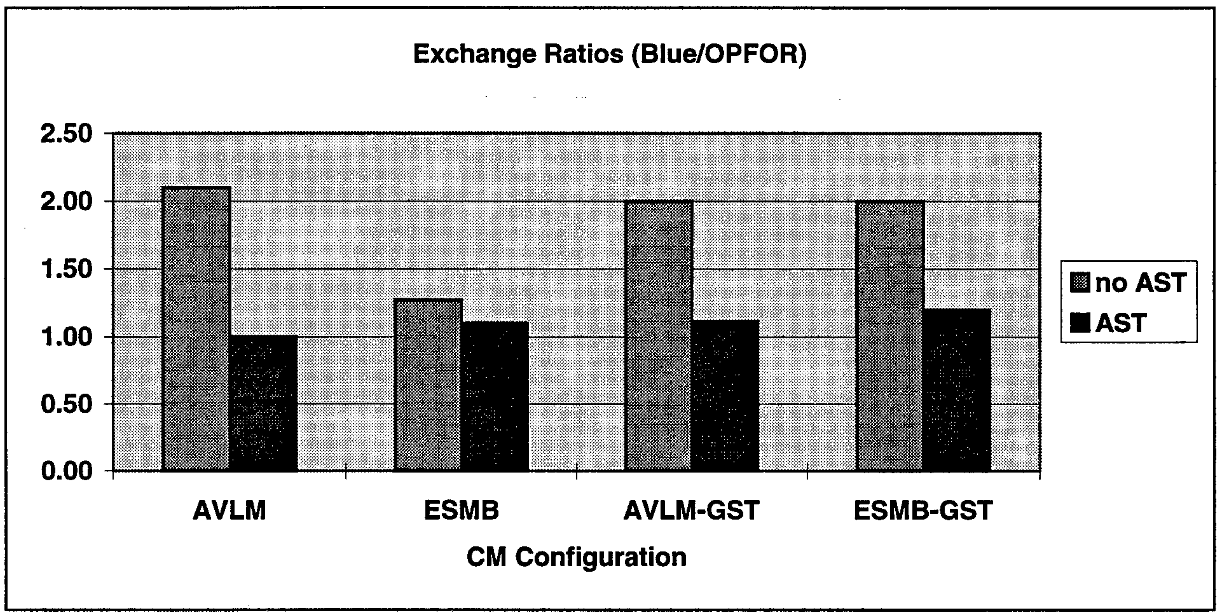

Figure 4. Loss Exchange Ratio

C. INTERACTIONS

In a factorial design, the working hypothesis is that the expected outcome in a given trial is a sum of components, one from each main factor plus a collection of "cross"

terms that represent interaction among the factors. The observed outcome is this expected value plus a random error. This section is a detailed discussion of the interactions among the countermine systems that are the major factors in this experiment.

Since the various types of countermine equipment used in these experiments would typically be used in concert with one another, (e.g., a breacher would be fired where a detection system indicated a minefield exists), some evidence of interaction is expected. A measure of the interaction between two factors, say ground surveillance and breaching systems, is obtained by comparing the average outcomes at the high and low levels of each factor. More precisely, interaction is measured by comparing the differences in outcomes between the high and low levels of one factor at each of the two levels of the second factor. Heuristically, this is equivalent to, first, collapsing the cube in Figure 2 along its vertical axis and computing average outcomes for each of the vertices of the resulting square. Then, select opposite edges of the square and compare the difference in outcomes between vertices on one edge with the difference on the other. The extent to which these two deltas differ determines the degree to which the factors interact.

For example, Table 6 below shows average Blue losses with and without GSTAMIDS for the cases in which AVLM was available and those in which ESMB was available. The bottom row (denoted "Delta") shows the difference between losses with and without GSTAMIDS for runs with AVLM and runs with ESMB.

Table 6. Interaction Between Ground Surveillance and Breaching Systems

Blue Losses	By All Agents		By DF+IF		By Mines	
	AVLM	ESMB	AVLM	ESMB	AVLM	ESMB
No GST	3.875	3.125	1.625	1.75	2.25	1.375
GST	4	3.75	2.5	2.75	1.5	1
Delta	-0.125	-0.625	-0.875	-1	0.75	0.375

For a given category of agent, say mines, the deltas are 0.75 and 0.375. These two values are too close to suggest any significant interaction between ground surveillance and breaching system. A more precise indication of significance will appear in the ANOVA tables of a later section. The following graph, Figure 5, gives a pictorial

representation of the data in Table 6. The distance between the ends of the line segments are the deltas. The interaction is the extent to which the lines diverge from parallel.

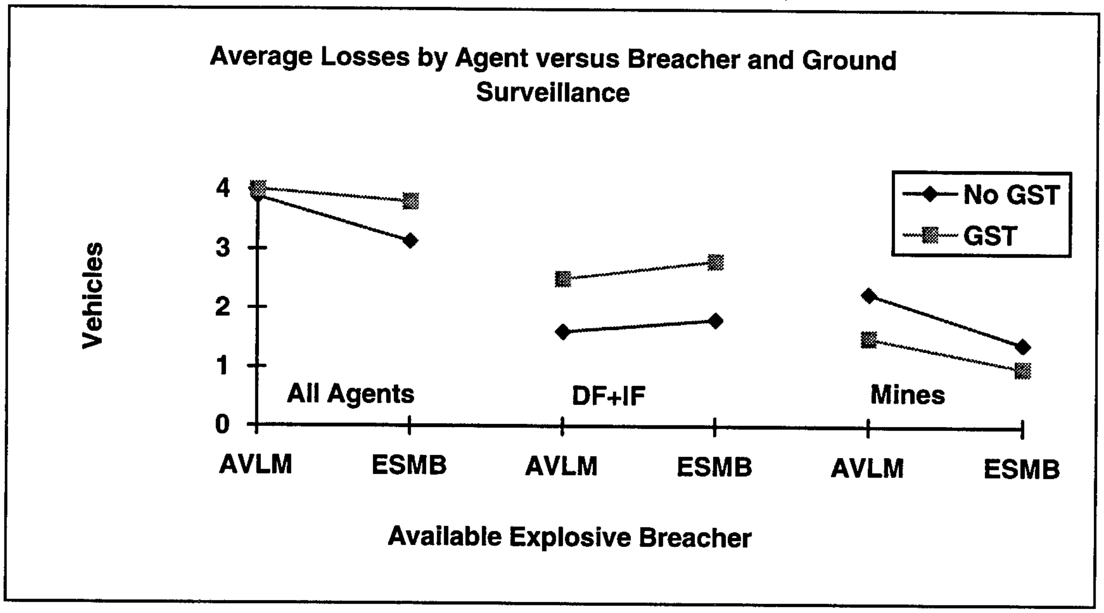

Figure 5. Graphical Representation of Interaction Between Ground Surveillance and Breaching Systems

Interactions between aerial surveillance and breaching systems are markedly different from the previous case, as can be seen in Table 7. For example, when AVLM is available, losses to mines are considerably greater without ASTAMIDS than with ASTAMIDS. But, on the other hand, when ESMB is available, aerial surveillance does not appear to affect losses to mines. Thus deltas differ, indicating an interaction between these factors. Some level of interaction exists with respect to the other measures, losses to all agents and losses to direct and indirect fire, also. However, it is not as pronounced as the losses to mines.

Table 7. Interactions Between Aerial Surveillance and Breaching Systems

Blue Losses	By All Agents		By DF+IF		By Mines	
	AVLM	ESMB	AVLM	ESMB	AVLM	ESMB
No AST	5.375	4	2.125	2.75	3.25	1.25
AST	2.5	2.875	2	1.75	0.5	1.125
Delta	2.875	1.125	0.125	1	2.75	0.125

A striking feature in Figure 6, below, is the huge decrease in losses to mines (and to all agents combined) realized when ASTAMIDS is used in conjunction with AVLM. This bears some scrutiny and skepticism for the following reason. Recall that there are eight runs in which ASTAMIDS and AVLM were both available to Blue. In only two of these did Blue actually deploy AVLM: in the remaining six, Blue circumvented minefields detected by ASTAMIDS. Without ASTAMIDS, Blue initiated breaching operations with AVLM in five out of eight runs. With ESMB, Blue initiated breaching operations in five out of eight trials with ASTAMIDS and in five out of eight trials without ASTAMIDS (Blue also conducted breaching operations with rollers and plows in two additional runs: in at least one of which ESMB was destroyed by mines.) While a comparison of breaching and bypassing minefields will be the subject of a later analysis section, it is worth saying at this point that losses to mines were, on average, 2.2 vehicles in runs where breaching operations were attempted, and 0.54 where they were not. Losses to direct and indirect fire were about the same (2.15) in each case.

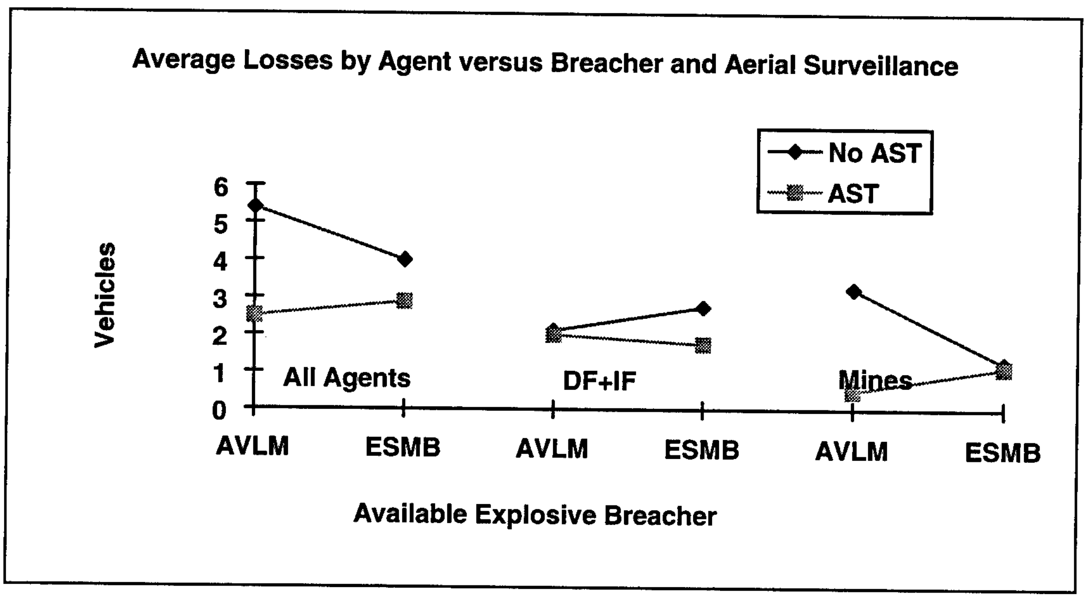

Figure 6. Graphical Representation of Interactions Between Aerial Surveillance and Breaching Systems

Aerial and ground surveillance make up the final system pair to be considered. As shown in Table 8, the most interesting interaction appears in terms of losses to direct and indirect fire. Without GSTAMIDS, there is little difference between having or not having aerial surveillance. With GSTAMIDS, there appears to be, relatively, a large difference.

Table 8. Interactions Between Aerial and Ground Surveillance Systems

Blue Losses	By All Agents		By DF+IF		By Mines	
	No GST	GST	No GST	GST	No GST	GST
No AST	4.375	5	1.625	3.25	2.75	1.75
AST	2.625	2.75	1.75	2	0.875	0.75
Delta	1.75	2.25	-0.125	1.25	1.875	1

The graph in Figure 7 demonstrates the interaction fairly vividly. Since the deltas for direct and indirect fire have different signs, the graphs of average losses intersect. Generally speaking, this is the signature of interaction between systems.

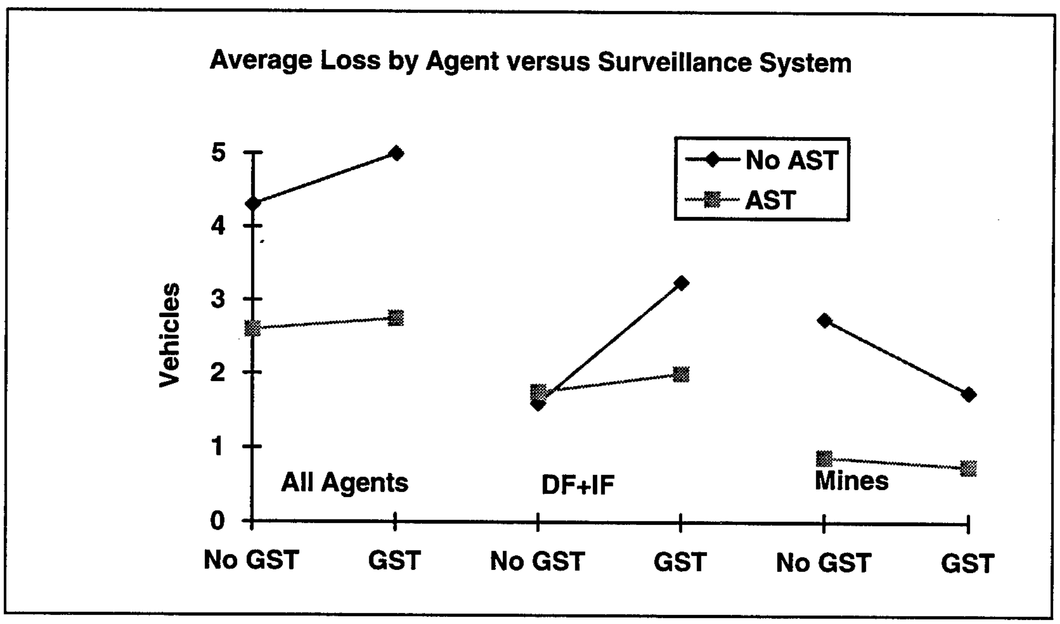

Figure 7. Graphical Representation of Interaction between Aerial and Ground Surveillance Systems

The reason for the observed effect is less clear than in the previous case regarding AVLM and ASTAMIDS. Here, ASTAMIDS has some payoff for Blue in general, while GSTAMIDS appears to be associated with an increase in losses to direct and indirect fire when used without aerial surveillance. This observation may be related to the amount of time the Blue force spent in an exposed position while GSTAMIDS searched for the leading edge of the minefield in preparation for launching an explosive breacher or, possibly, for gaps between the fields. This issue bears further investigation and may be an appropriate focus for a constructive model.

D. ANALYSIS OF VARIANCE

This section is an attempt to put some of the tables and graphs in the previous section on a statistical footing. The primary mechanism to be used is classical analysis of variance (ANOVA) because the exercise is based on a balanced factorial design and lends itself easily to this technique. As used here, ANOVA decomposes the sum of squared deviations of Blue losses over the entire experiment into components associated with the breacher, the two detection systems, and their interactions. This decomposition enables the analyst to isolate the most influential effects by performing one test. An F-statistic relates each component (of the sum of squares) to the probability that deviations as large as those observed would occur by chance. A large value of F (depending on the degrees of freedom involved) indicates a significant outcome. For example, in the tables of F-statistics given below, the large values accompanying aerial surveillance are indicative of the impact this system has on Blue losses.

Complete ANOVA tables for all factors and interactions is deferred until Appendix B. Only the F-statistics and the corresponding principal factors and interactions are presented here. In keeping with the previous format, tables are shown for total Blue losses, losses due to direct and indirect fire combined, and losses to mines.

Table 9. F-Statistics for Main Effects and Interactions

Source of Variation	F- Statistics		
	Losses To All Agents	To DF+IF	To Mines
Breaching System (BR)	0.2	0.084	1.12
Ground Surveillance	0.11	2.1[a]	0.75
Aerial Surveillance	3.12[b]	0.76	4.88[c]
Interact (BR - Ground)	0.05	0.0093	0.08
Interact (BR and Aerial)	0.6	0.46	4.07*
Interact (Aerial-Ground)	0.05	1.13	0.45
Interact (BR-Ground-Aerial)	0.12	0.23	0.83
R^2	0.147	0.166	0.323

[a] Increases to 3.38, which is significant at the 10% level, when variance due to replications (area) is taken into account (see Section F and Appendix B).

[b] Significant at the 10% level.

[c] Significant at the 5% level.

Table 9 indicates that the factor having greatest impact on losses to all agents and losses to mines is aerial surveillance. This is in keeping with the discussion following Figure 3, which showed that mean losses with and without ASTAMIDS differed significantly. As indicated in the earlier discussion, variations due to other systems do not have as great an impact. Interactions were significant between aerial surveillance and breaching systems (with respect to losses to mines and all agents), but not between aerial and ground surveillance as anticipated in the last section—even with respect to losses to direct and indirect fire. Again, this indicates that the difference in outcomes with and without ASTAMIDS varies so greatly from AVLM to ESMB, that the variation is unlikely to be ascribed to chance. However, the corresponding differences for aerial and ground surveillance, even for losses to direct and indirect fire, are not large enough when compared to the random behavior of the system to be considered significant.

A word of caution regarding the impact of aerial surveillance is appropriate. Since there is significant interaction between aerial surveillance and breaching systems, the actual effect of aerial surveillance is not estimable without the somewhat artificial constraint that indexed terms sum to zero in the linear model (Searle, *Linear Models for Unbalanced Data*, John Wiley, 1987, pp. 331-332). The difficulty lies in the fact that the mean effects of the two levels of aerial surveillance cannot be separated from the influence of the breachers.

In Section II. C, above, there is some discussion of a possible link between the improved outcomes when Blue deployed ASTAMIDS and AVLM, and the tendency to

conduct bypassing or minefield avoidance operations when these two systems were available. Table 9 reaffirms this observed effect in terms of the F-statistic. Because of the technical evidence of this interaction and its possible relation to decisions to conduct bypass operations, Night Vision Laboratory requested that the experiment be re-examined from the standpoint of a factorial design in which the tactic, bypassing or breaching, is examined as a main effect with two levels. A variation of this approach is the subject of a later section.

Before continuing on to the next section, however, it may be of interest to compute the regression coefficients of the model proposed in Section I.E, above. These coefficients belong to the model dictated by the 2^3 factorial design and correspond to the variables (including a constant term) contained in Table 10.

Table 10. Regression Coefficients for Main Effects and Interactions

	Value of Regression Constant or Coefficient		
	Losses To All Agents	**To DF+IF**	**To Mines**
u (constant)	3.69	2.156	1.53
a_0 aerial surveillance	1.0	0.281	0.719
b_0 breaching system	0.25	-0.094	0.344
g_0 ground surveillance	-0.187	-0.469	0.281
ab_{00} Interact (BR and Aerial)	0.438	-0.219	0.656
bg_{00} Interact (BR - Ground)	0.125	0.0313	0.094
ga_{00} Interact (Aerial-Ground)	-0.125	-0.344	0.219
w_{000} Interact (BR-Ground-Aerial)	0.0625	0.156	-0.094

The zero subscript in the above table denotes the lower level of the system (e.g., a_0 means ASTAMINDS is not used). The remaining coefficients, such as a_1, are determined from the constraints ($\Sigma\ a_i\ = 0$, etc.) introduced with the linear model in Section I.E, Factorial Design. For example, a_1 = -1.0 when the measure is "loss to all agents" and -0.72 when the measure is "loss to mines." Taking this a step further, the expected loss to all agents under the full linear model without ASTAMIDS, GSTAMIDS, or ESMB is

$$E(y_{000n}) = 3.69 +1.0 +0.25 -0.187 + 0.438 +0.125 -0.125 + 0.0625 = 5.25;$$

when ASTAMIDS is included, the expected loss becomes

$$E(y_{100n}) = 3.69 -1.0 + 0.25 -0.187 - 0.438 + 0.125 + 0.125 - 0.0625 = 2.5.$$

Both of these agree with the average observed outcomes, as is the case for all remaining cells, also.

E. LEARNING

A natural question in tests of this sort is whether or not learning had a measurable impact. In the first half of the trials, Blue's losses to all agents were, on average, 3.6 vehicles per trial. In the second half, it was about 3.8. Losses to mines were about 1.56 and 1.5 vehicles per trial in the first and second halves, respectively. Finally, losses to direct and indirect fire were 2.04 vehicles per trial in the first half and 2.3 in the second. These data seem to indicate that learning was not a factor. However, since the systems used in the second half were different from those used in the first, an analysis that takes the different systems into account needed to be performed. Consequently, a stepwise regression algorithm was applied in which the starting variables are those of the linear model plus the sequence in which the test trials occurred (see Table 4). The algorithm (provided in SPSS version 7.5), which only enters variables with less than a 10% level of significance, yields the set of coefficients and F-statistics appearing below in Tables 11 and 12.

Table 11. Stepwise Regression Constant and Coefficients

	Value of Regression Constant or Coefficient		
	Losses To All Agents	To DF+IF	To Mines
u (constant)	3.69	2.156	1.53
a_0 (aerial)	1.0		0.719
ab_{00} (aerial-breaching system interact)			0.656

Table 12. F-Statistics Corresponding to Stepwise Regression

	F-statistics		
	Losses To All Agents	To DF+IF	To Mines
a_0 (aerial)	3.74		5.35
ab_{00} (aerial-breaching system interact)			4.46

As the "learning" covariate does not appear in the tables, the order of the trials was apparently not a significant factor. This contention is also supported by other regression analyses in which terrain, that is, scenario area, and tactics are taken into

account. On the other hand, one might argue that the effect attributed to ASTAMIDS might be, in part, a learning effect because the ASTAMIDS runs usually followed (by about two days) the corresponding runs without ASTAMIDS and minefields were deployed identically in corresponding cases. R^2, the portion of the variance accounted for by regression, in the above tables are 0.11, 0.6, and 0.25, respectively.

F. SCENARIO AREAS (REPLICATIONS)

Four different scenarios (taking place on four different areas of terrain) were used in these trials. Each involved the same number of Blue and OPFOR units, but differed somewhat with respect to the number of minefields. On average Area 1 contained 4.25 fields, Area 2 contained 4, Area 3 contained 5, and Area 4 contained 4.25. Every minefield was 200 m by 100 m and each contained 140 AT mines and 80 AP mines. Blue forces traveled about the same distance in all cases; but some variation in terrain was apparent from maps of the four areas. When trials were grouped by these geographic areas, they differed with respect to outcomes.

Figure 8 suggests a strong difference between outcomes of trials taking place on Area 1 and the three other terrain patches in CME. Losses in all categories are greater on average in Area 1. Also, there is some uniformity with respect to losses to mines among the remaining three, while losses to direct and indirect fire show some variation. While a definitive explanation of why Area 1 stands out may prove elusive, some simple conjectures come to mind quickly. One is that the runs were conducted in order with respect to areas. Thus, the Blue force's first exposure to a given mix of countermine equipment occurred on Area 1. There was only one exception to this practice, which occurred in the second vignette when an Area 1 trial was run after the corresponding trials on Areas 2, 3, and 4. It seems reasonable to suspect that learning may account for the higher losses associated with Area 1. (Recall that an elementary regression-based analysis indicated no influence of the overall order of runs on the number of Blue losses.)

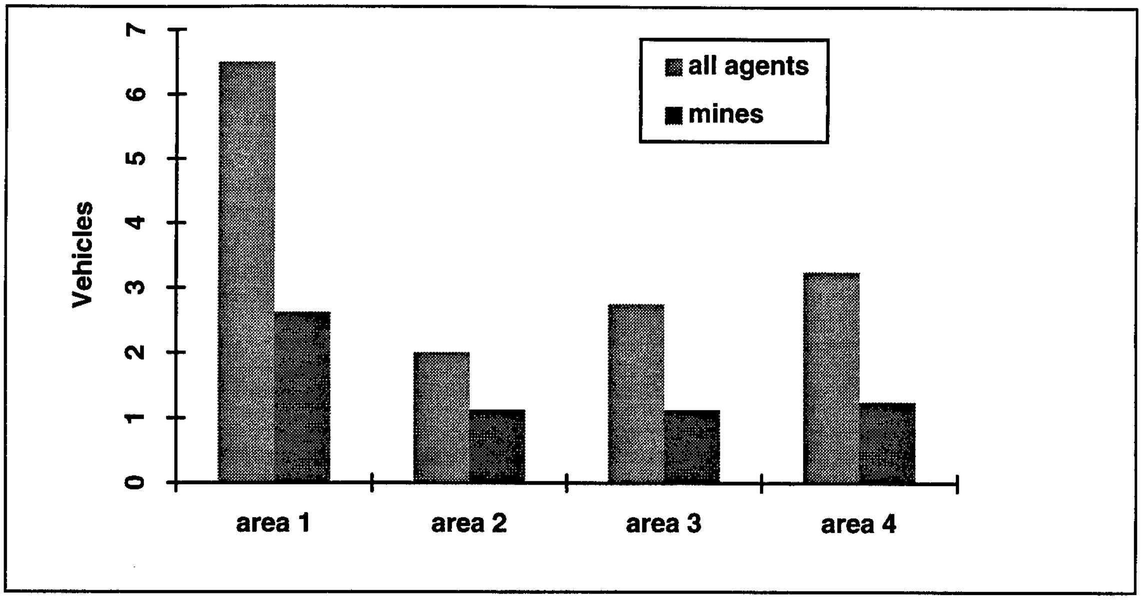

Figure 8. Blue Losses Vs Area (Scenario)

Another conjecture about the vulnerability of Blue forces in Area 1 has to do with the "lay of the land." In Area 1, Blue was required to traverse a corridor (the long axis of a low-lying basin) in order to secure its objective. This topographical feature may have exposed Blue to direct fire and channeled its forces in some way that made them less able to avoid mines. All other terrain sections were planar or irregular and may have afforded Blue more lateral movement. In any case, they did not channel the Blue force to the same extent as Area 1.

Appendix B contains the sum of squares due to replications (scenario areas) and the error sum of squares from which ANOVA tables for factors and interactions can be computed after variations due to replications are taken into account. These modified ANOVA tables reveal that aerial surveillance and the interaction between aerial surveillance and breaching system become more significant with respect to losses to mines and all agents combined, while ground surveillance becomes significant with respect to losses to direct and indirect fire (in the sense that GSTAMIDS increases losses). Essentially the same issue is addressed here, but the analysis mechanism is stepwise regression with scenario areas introduced as covariables to the basic linear model.

The following tables contain data related to the impact of scenarios in the analysis of the of countermine systems. Again, stepwise regression was used to fit the linear

model in Section I.E with covariates representing the four individual areas, the resulting expression for the expected outcome on the 'm'th area (1,2,3, or 4) now becomes

$$E(y_{ijkmn}) = u + a_i + b_j + g_k + s_m + ab_{ij} + bg_{jk} + ga_{ki} + w_{ijk}$$

In this formulation, s_m is not constrained by the summation condition that applies to the other variables.

Table 13. F-Statistics for Model with Scenario Area

Source of Variation	F- statistics		
	Losses To All Agents	To DF+IF	To Mines
Area (Scenario)	14.2	15.8	4.6
Aerial Surveillance	5.4		6.0
Ground Surveillance		3.53*	
Interact (Breaching System - Aerial)			5.0
R^2 (Adjusted R^2)	0.40 (0.36)	0.40 (0.36)	0.36 (0.29)
Durbin-Watson	2.4	1.68	2.9

* The value of F differs from that given below the ANOVA Table 9 (3.38) because the former used the full linear model, whereas here stepwise regression reduced the model to a constant plus two coefficients.

Scenario area is clearly an important factor in all of the measures addressed in Table 13. Aerial surveillance impacts both losses to mines and overall losses, whereas ground surveillance is a significant factor with respect to losses to direct and indirect fire. That is, while the use of ASTAMIDS reduces Blue losses to mines and all agents, the use of GSTAMIDS increases losses to direct and indirect fire. Again, the increase in losses may be due to the increased exposure of Blue forces while they search for minefields or gaps between fields. The GSTAMIDS vehicle was a casualty in only one of the eight trials in which it was deployed, so the increased losses are not entirely due to the presence of an extra vehicle. Quantitatively, the impact of GSTAMIDS is manifested by the negative coefficient corresponding to the *absence* of a ground surveillance system in Table 14, below.

Table 14. Regression Coefficients for Model with Scenario Areas

	Value of Regression Term or Coefficient		
	Losses To All Agents	To DF+IF	To Mines
u - Constant	2.75	1.58	1.17
s_1 - Area 1	3.75	2.29	1.46
a_0 - Aerial Surveillance	1.0		0.72
g_0 - Ground Surveillance		-0.47	
ab_{00} - Interact (Breaching System - Aerial)			0.66

G. TACTICS

In order to investigate the impact of tactics, it was necessary to first identify those trials in which breaching or bypassing took place. While one would expect this to be entirely straightforward, it does contain an element of ambiguity. Most trials in which breaching occurred contain at least one launch of either AVLM or ESMB. However, as mentioned earlier, rollers and plows were deployed in lieu of ESMB in two trials. Also, in one trial in which AVLM was launched in anticipation of a breaching operation, a bypass route was discovered and the breaching operation was abandoned. In another, after AVLM was launched and breaching initiated, losses mounted so quickly that Blue withdrew from the field and never achieved the objective.

Nonetheless, launches and breaching attempts are highly correlated. Table 15 lists all the trials and describes each in terms of whether or not a breaching operation was initiated. Breach attempts are shown in shaded boxes, while trials with bypassing operations are shown as clear.

Table 15. Breaching and Bypassing

					AST	AST	AST	AST
	area 1	area 2	area 3	area 4	area 1	area 2	area 3	area 4
AVLM (base case)	breach	pass	breach[a]	breach	pass	pass	breach	pass
ESMB	breach	breach[b]	breach[b]	breach	pass	breach	breach	breach
AVLM-GST	pass	breach	pass	breach[c]	pass	pass	pass	breach
ESMB-GST	pass	breach	breach	breach	breach	breach	pass	pass

[a] Blue withdrew after launching AVLM.

[b] Breach operations conducted with rollers and plows only.

[c] Blue finds bypass after launching AVLM.

From Table 15, Blue initiated 19 breach and 13 bypass operations. Four bypasses were conducted without ASTAMIDS, and five were conducted without GSTAMIDS. Only one was conducted with neither surveillance system. On the other hand, bypassing was initiated nine times in the presence of ASTAMIDS, eight times with GSTAMIDS, and five times with both. Thus, roughly speaking, there was a 50% empirical probability of bypassing (12 occurrences out of a possible 24) when some sort of surveillance system was available, but only about 12% when there was none.

A simple 2x2 contingency table confirms that the availability of aerial surveillance information is a significant factor in the choice of tactics. Surprisingly, the

availability of ground surveillance is not (at least, not nearly to the same degree). While the count differences are small, there may be a basic difference between the way ASTAMIDS and GSTAMIDS are used that ties the aerial system more closely to bypassing. ASTAMIDS was a reconnaissance tool deployed in the first phase to select routes, whereas GSTAMIDS may have been used more to locate the edge of minefields after routes had been partially traversed.

Table 16 contains the number of times Blue chose (or at least prepared to) to breach and the number of times Blue chose to bypass or circumvent minefields depending on whether or not ASTAMIDS data were available. The standard Pearson's Chi-square statistic equals 3.24, which is significant below the 10% level (suggesting availability of aerial surveillance data and tactical decisions are not independent).

Table 16. Influence of Aerial Surveillance and Breaching Systems on Choice of Tactics (contingency tables)

	No Aerial Surveillance	**ASTAMIDS**
Breaching Tactic	12	7
Bypassing Tactic	4	9
	AVLM	**ESMB**
Breaching Tactic	7	12
Bypassing Tactic	9	4

A similar table for AVLM vs. ESMB has the identical entries and therefore the same Chi-square, indicating that that type of explosive breaching system may have had a strong influence on tactics. Finally, the very last table (below, Table 17) indicates that there is very little impact on choice of tactics due to the availability of a ground surveillance system. In this case, the Chi-square is 1.17, which is not significant even at the 25% level.

Table 17. Influence of Ground Surveillance System on Choice of Tactics

	No Ground Surveillance	**GSTAMIDS**
Breaching Tactic	11	8
Bypassing Tactic	5	8

These results were confirmed by stepwise regression, which indicated that the significant factors determining tactics were aerial surveillance and type of explosive breaching system. Bypassing was the more likely tactic when AVLM was the breacher and ASTAMIDS data were on hand.

The remainder of this section discusses Blue losses as a function of chosen tactic. We begin with Table 18, which lists the mean losses by agent for breaching and bypassing. The same table with standard errors of the means appears in Appendix C (from which one can determine, say, that the difference in mean losses to mines is significant below the 10% level).

Table 18. Blue Losses Versus Countermine System and Tactic

Blue Losses	Breach	Bypass
By Mines	2.21	0.54
By D.F.+ I.F.	2.16	2.15
Total	4.37	2.69

It is not surprising that Table 18 shows a substantial decrease in losses to mines as tactics shift from breaching to bypassing. After all, bypassing suggests avoiding mines by either circumventing minefields or penetrating through gaps between fields. Mine encounters should only occur when field positions are incorrectly estimated or when vehicles wander from designated paths. Of the 13 bypass cases, 3 contained losses to mines (all in Area 1). In two of these, three vehicles were lost in each run; one vehicle was lost in the third. In each of these three cases some form of surveillance system was available (two with GSTAMIDS, one with ASTAMIDS). In neither case were both available.

Mean losses to all agents differ substantially, but this difference is due to the differences in losses to mines. Somewhat surprisingly, the mean losses to direct and indirect fire for both breaching and bypassing are almost identical. It is not clear why this should be so, but the explanation may involve the fact that Blue forces spend a good deal of effort searching for gaps between fields when attempting minefield avoidance. The resulting exposure to enemy fire while searching may be comparable to the exposure endured while breaching.

The impact of tactics was analyzed by using breaching and bypassing as covariables to the standard model. That is, in addition to the nine terms used in the

regression in Section II.F, a tenth term was added to account for tactics. Thus the resulting model becomes

$$E(y_{ijkmnp}) = u + a_i + b_j + g_k + s_m + t_n + ab_{ij} + bg_{jk} + ga_{ki} + w_{ijk}$$

where t_0 represents breaching and t_1 represents bypassing.

The following abbreviated table shows the results of a stepwise regression in which tactic, along with the countermine systems and their interactions, is a variable. A standard 10% level of significance is used as an entry criterion, so that all variables represented are significant at that or a lower level.

Table 19. F-Statistics with Tactics, Techniques, and Procedures (TTP) + Area Model

Source of Variation	F- Statistics		
	Losses To All Agents	To DF+IF	To Mines
Tactic	13.8		24.5
Area (Scenario)	25.3	15.8	15.6
Ground Surveillance		3.53[a]	
Breaching System	3.36		9.16
Interact (Breaching System - Aerial)			6.06
R^2 (Adjusted R^2)	0.53 (0.48)	0.633 (0.359)	0.61 (0.55)
Durbin-Watson	2.16	1.68	2.66

[a] The value of F differs from that given below the ANOVA Table 9 (3.38) because the former used the full linear model, whereas here stepwise regression reduced the model to a constant plus two coefficients.

Table 19 suggests that tactics and terrain are the most important considerations with respect to losses to mines and all agents combined. Also, as in the case of the previous model, which only considered variations due to replications (area), terrain and ground surveillance had significant impact on losses to direct and indirect fire. The greatest surprise in Table 18 is the disappearance of aerial surveillance/reconnaissance as a significant factor with respect to losses to mines and all agents. This is most likely due to the fact that bypassing and the availability of ASTAMIDS data are so closely related. More precisely, although aerial surveillance is highly correlated with losses to mines (correlation coefficient is 0.37, which is significant at about the 3.6% level), tactics is even more highly correlated (0.42, significant at the 1.6% level). More importantly, however, when one controls for tactics (in effect, determine correlation when tactics are held fixed), the partial correlation of aerial surveillance with losses to mines drops to

0.28, which is only significant at the 13.4% level. On the other hand, when one controls for aerial surveillance, tactics and losses to mines remain significantly correlated (0.35, significant at 5.5%). This is essentially the process through which stepwise regression computes the most relevant factors. A similar argument holds for losses to all agents combined.

The appearance of breaching system as a significant factor is not terribly surprising; recall, Blue losses averaged about 0.5 vehicles higher with AVLM than with ESMB, overall, and 0.7 with respect to mines. The interaction between aerial surveillance and breaching system remains significant, however. The same cautionary note expressed in Section II.D regarding interactions and main effects must be repeated here. The fact that significant interaction exists between the level of aerial surveillance and breaching system (with respect to losses to mines) implies that the impact of breaching systems depends on the level of aerial surveillance and cannot be estimated without imposing the constraint that interactions sum to zero (over each index). The extent to which the reader can accept this constraint has bearing on the extent to which he or she is willing to accept the conclusion.

Table 20 contains the regression coefficients for each of the significant terms for each of the measures: losses to all agents, direct and indirect fire, and mines. Again, as in Section II.D, a zero subscript connotes the lower level of the system (e.g., 'g_0'means GSTAMINDS is not used and 'b_0' implies AVLM). Recall, the symbol 't_0' denotes the breaching tactic. Positive coefficients indicate an increase in losses. Again, the appearance of a negative coefficient for ground surveillance with respect to losses to direct and indirect fire indicates that these losses are reduced without GSTAMIDS.

Table 20. Stepwise Regression Constants and Coefficients with TTP + Area Model

	Value of Regression Term or Coefficient		
	All Agents	DF + IF	Mines
u - Constant	2.2	1.58	0.74
t_0 - Tactic	1.6		1.29
S_1 - Area	4.7	2.3	2.2
b_0 - Breaching System	0.75		0.74
g_0 - Ground Surveillance		-0.47	
ab_{00} - Interact (Aerial - Breaching System)			0.58

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III. CONCLUSIONS AND RECOMMENDATIONS

Three points stand out from the analyses of CME data. First, having ASTAMIDS intelligence reduced losses due to mines and all agents combined. This was due, at least in part, to the fact that bypassing as a tactic was employed at a relatively high frequency when ASTAMIDS data were available.

Secondly, the use of GSTAMIDS is costly with respect to losses from direct and indirect fire, especially in breaching operations. Unsurprisingly, Blue's losses to mines can be reduced by circumventing or penetrating gaps between minefields without any apparent increase in losses to direct or indirect fire.

Finally, there appears to be a strong interaction—with respect to Blue losses to mines—between aerial surveillance and the explosive breaching system. This is likely to be due to the fact that bypassing was the preferred tactic when AVLM and ASTAMIDS data were available. The possibility of a tendency (perhaps ascribable to the desire to exercise a new system) to breach when ESMB was on hand should not be discounted. When tactics are taken into consideration, ESMB reduces losses to mines, however.

These issues should be investigated in greater detail. An appropriate research mechanism might be a constructive model in which large numbers of trials can be generated. It is highly recommended that future test designs include tactics (breaching versus bypassing) as a principal factor.

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APPENDIX A
BLUE LOSSES AND PARTIAL KILLER-VICTIM SCOREBOARDS

Appendix A
BLUE LOSSES AND PARTIAL KILLER-VICTIM SCOREBOARDS

Table A-1. Blue Losses to Mines

	No ASTAMIDS				ASTAMIDS			
	area 1	area 2	area 3	area 4	area 1	area 2	area 3	area 4
AVLM	8	0	6	1	3	0	0	0
ESMB	2	1	3	1	0	2	0	2
AVLM-GSTAMIDS	3	4	0	4	0	0	0	1
ESMB-GSTAMIDS	1	1	0	1	4	1	0	0

Table A-2. Blue Losses to Direct and Indirect Fire

	No ASTAMIDS				ASTAMIDS			
	area 1	area 2	area 3	area 4	area 1	area 2	area 3	area 4
AVLM	4	0	2	0	5	1	1	0
ESMB	2	0	2	3	4	0	1	2
AVLM-GSTAMIDS	5	1	2	3	3	3	1	2
ESMB-GSTAMIDS	3	2	3	7	5	1	1	0

Table A-3. Data for Figure 1

Kills	AVLM	AVLM-AST	ESMB	ESMB-AST	AVLM-GST	AVLM-GST-AST	ESMB-GST	ESMB-GST-AST
By Mines	3.75	0.75	1.75	1	2.75	0.25	0.75	1.25
By D.F.	1.5	1.5	1.75	1.25	2	0.75	2.5	1.25
By I.F	0	0.25	0	0.5	0.75	1.5	1.25	0.5
Total	5.25	2.5	3.5	2.75	5.5	2.5	4.5	3

Losses were computed by counting all vehicles that had at least one of the standard damage levels: mobility, fire power, or catastrophic. For vehicles suffering only mobility and fire-power kills, credit was ascribed to the agent inflicting the first kill. In the case of vehicles suffering mobility or firepower followed by a subsequent catastrophic kill, the agent inflicting the catastrophic kill was given credit.

The following table is an abbreviated killer-victim scoreboard. All Blue vehicles are represented, but not in all possible subcategories. Categories presented are: Manned Armor Vehicles, which are the M1A1s containing live tank crews; simulated ModSAF M1A1s, referred to as the Simulated Armor Vehicles; M1A1s with rollers and plows, which were simulated in ModSAF; Blue countermine and engineering vehicles, both manned and simualted.

Table A-4. Killer - Victim Scoreboard

	AVLM	AVLM-AST	ESMB	ESMB-AST	AVLM-GST	AVLM-GST-AST	ESMB-GST	ESMB-GST-AST
Blue Armor (Manned M1A1s)								
by mines	1	0.5	0.75	0	0	0	0	0.75
by DF	0	0	0	0	0	0	0	0
by IF	0	0	0	0	0	0	0	0
Blue Armor (Simulated M1A1s- without plows and rollers)								
by mines	1	0	0	0	1	0	0.5	0
by DF	0.75	0.5	1.75	0.5	0.5	0.5	2	1
by IF	0	0.25	0	0.25	0.25	0	0.5	0.25
Blue Armor (Simulated M1A1- with plows and rollers)								
by mines	0.75	0.25	0.5	0.75	1	0	0.25	0.5
by DF	0.75	1	0	0.75	1	0.25	0.5	0.25
by IF	0	0	0	0	0.25	0.25	0.25	0.25
Blue Countermine and Engineering Vehicles (Manned and Simulated)								
by mines	1	0	0.5	0.25	0.75	0.25	0	0
by DF	0	0	0	0	0.5	0	0	0
by IF	0	0	0	0.25	0.25	1.25	0.5	0

Total	5.25	2.5	3.5	2.75	5.5	2.5	4.5	3
Mines	3.75	0.75	1.75	1	2.75	0.25	0.75	1.25
DF	1.5	1.5	1.75	1.25	2	0.75	2.5	1.25
IF	0	0.25	0	0.5	0.75	1.5	1.25	0.5

APPENDIX B
ANOVA TABLES

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ANOVA TABLES

Table B-1. ANOVA for Blue Losses to All Agents

Source of Variation	Sum of Squares	D.F.	Mean	F
Breaching System	2	1	2	0.2
Ground Surveillance	1.125	1	1.125	0.11
Aerial Surveillance	32	1	32	3.12[a]
Interact (breacher-ground)	0.5	1	0.5	0.05
Interact (breacher-aerial)	6.125	1	6.125	0.6
Interact (ground-aerial)	0.5	1	0.5	0.05
Interact (all)	0.125	1	0.125	0.012
Error	246.5	24	10.27	
Total	288.875	31		

[a] Significant at 10% level; becomes 4.31 when variance due to replications (areas) is taken into account. (The sum of squares due to replications is 90.6, with 3 degrees of freedom.)

Table B-2. ANOVA for Blue Losses to Mines

Source of Variation	Sum of Squares	D.F.	Mean	F
Breaching system	3.78	1	3.78	1.12
Ground surveillance	2.53	1	2.53	0.75
Aerial surveillance	16.53	1	16.53	4.88[a]
Interact (breacher-ground)	0.28	1	0.28	0.08
Interact (breacher-aerial)	13.78	1	13.78	4.07[b]
Interact (ground-aerial)	1.53	1	1.53	0.45
Interact (all)	0.28	1	0.28	0.83
Error	81.25	24	3.385	
Total	119.97	31		

[a] Significant at 5% level; becomes 5.08 when variance due to replications is taken into account.

[b] Significant at 10% level; becomes 4.23 when variance due to replications is taken into account.

(The sum of squares due to replications is 12.8, with 3 degrees of freedom.)

Table B-3. ANOVA for Blue Losses to Direct and Indirect Fire

Source of Variation	Sum of Squares	D.F.	Mean	F
Breaching System	0.28	1	0.28	0.084
Ground Surveillance	7.03	1	7.03	2.1[a]
Aerial Surveillance	2.53	1	2.53	0.76
Interact (breacher-ground)	0.31	1	0.31	0.0093
Interact (breacher-aerial)	1.53	1	1.53	0.46
Interact (ground-aerial)	3.78	1	3.78	1.13[b]
Interact (all)	0.78	1	0.78	0.23
Error	80.25	24	3.34	
Total	96.2	31		

[a] Becomes 3.38 when variance due to area is taken into account (10% level of significance).

[b] Becomes 1.82 when variance due to area is taken into account.

(The sum of squares due to replications is 36.6, with 3 degrees of freedom.)

APPENDIX C
PAIRWISE COMPARISONS

Appendix C
PAIRWISE COMPARISONS

Table C-1 summarizes the mean number of kills of Blue vehicles by OPFOR agent. The first row shows the technology available in the 16 trials over which the kills were averaged. Pairwise t-tests show significant differences (below 10%) in the following cases: losses to mines with and without ASTAMIDS, overall losses with and without ASTAMIDS, and losses to direct and indirect fire with and without GSTAMIDS.

Table C-1. Mean Blue Losses by Agent Versus Countermine System (with standard error of the mean)

Blue Losses	AST	No AST	AVLM	ESMB	GST	No GST
By Mines	0.81 (0.32)	2.25 (0.57)	1.88 (0.63)	1.19 (0.29)	1.25 (0.39)	1.81 (0.58)
By D.F.+ I.F	1.88 (0.42)	2.44 (0.47)	2.06 (0.41)	2.25 (0.48)	2.63 (0.46)	1.69 (0.41)
Total	2.69 (0.65)	4.69 (0.80)	3.94 (0.91)	3.44 (0.61)	3.88 (0.69)	3.5 (0.85)

Table C-2 is a copy of Table 17 in the text with standard errors of the mean included for completeness.

Table C-2. Blue Losses Versus Countermine System and Tactic (mean and standard error of mean)

Blue Losses	Breach	Bypass
By Mines	2.21 (0.49)	0.54 (0.31)
By D.F.+ I.F.	2.16 (0.41)	2.15 (0.50)
Total	4.37 (0.72)	2.69 (0.76)

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The Countermine Experiment, conducted at the Mounted Warfare Testbed at Ft. Knox, KY in July of 1996 by the Night Vision Sensors Division of Ft. Belvoir, VA and the Engineer Battle Testbed of Ft. Leonard Wood, MO, was a classic 2^3 factorial experiment. It examined three classes of countermine systems in which each class had two representations. The three categories of countermine systems were aerial surveillance, ground surveillance, and explosive breaching systems. An analysis of variance performed on the number of Blue vehicles lost during this experiment indicates that the aerial surveillance system is the most significant factor in reducing Blue losses to mines.

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